Submitted to *The Astrophysical Journal.*
Preprint typeset using LaTeX style emulateapj v. 14/09/00

TWO EXTRA-SOLAR PLANETS FROM THE ANGLO-AUSTRALIAN PLANET SEARCH[1]

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Submitted to The Astrophysical Journal.

ABSTRACT

We report the detection of two new extra-solar planets from the Anglo-Australian Planet Search around the stars HD 142 and HD 23079. The planet orbiting HD 142 has an orbital period of just under one year, while that orbiting HD 23079 has a period of just under two years. HD 142 falls into the class of "eccentric" gas giants. HD 23079 lies in the recently uncovered class of "ϵ Ret-like" planets – extra-solar gas giant planets with near-circular orbits outside 0.1 a.u. The recent discovery of several more members of this class provides new impetus for the extension of existing planet searches to longer periods, in the search for Jupiter-like planets in Jupiter-like orbits.

Subject headings: planetary systems – stars: individual (HD142, HD23079)

1. THE ANGLO-AUSTRALIAN PLANET SEARCH

The Anglo-Australian Planet Search (AAPS) is a long-term planet detection program which aims to perform extra-solar planet detection and measurement at the highest possible precision. Together with programmes using similar techniques on the Lick 3 m and Keck I 10 m telescopes (Fischer et al. 2001; Vogt et al. 2000), it provides all-sky planet search coverage for inactive F,G,K and M dwarfs down to a magnitude limit of V=7.5. Initial results from this programme demonstrate that AAPS acheives long-term, systematic velocity precisions of 3 m s^{-1} or better (Tinney et al. 2001; Butler et al. 2001).

AAPS is being carried out on the 3.92 m Anglo-Australian Telescope (AAT), using the University College of London Echelle Spectrograph (UCLES) and an I_2 absorption cell. UCLES is operated in its 31 lines mm^{-1} mode. Prior to 2001 September, it was used with a MIT/LL 2048×4096 15μm pixel CCD, and since then has been used with an EEV 2048×4096 13.5μm pixel CCD. Our target sample includes 178 FGK stars with $\delta < -20°$ and V<7.5, and a further 23 M and metal enriched stars with V<11.5. Where age/activity information is available from R'_{HK} indices (see e.g., Henry et al. (1996); Tinney et al. (2002)) we require target stars to have $R'_{HK} < -4.5$ (corresponding to ages greater than 3 Gyr). The observing and data processing procedure follows that described in Butler et al. (1996) and Butler et al. (2001).

2. CHARACTERISTICS OF HD 142 & HD 23079

HD 142 (HR 6, HIP 522, GJ 4.2A, LHS 1020) is a chromospherically inactive (R'_{HK}=−4.92) G1IV star (Houck 1978; Tinney et al. 2002). Its Hipparcos parallax of 39.0±0.6 mas implies absolute magnitudes of M_V=3.66±0.03 (ESA 1997) and M_{bol}=5.55±0.05 (Alonso, Arribas & Martínez-Roger 1995) . The fundamental parameters of HD 142 have been examined via spectroscopy (Favata et al. 1997) and Strömgren *ubvy* photometry (see the compilation of Eggen (1998)). Spectroscopy derives [Fe/H]=+0.04±0.15 and T_{eff}=6025 K, while the photometry suggests [Fe/H]=−0.04, which is in agreement with the spectroscopy to within uncertainties. Based on interpolation between the evolutionary tracks of Fuhrmann et al. (1998, 1997), the mass of HD 142 is estimated to be 1.15±0.1$M_\odot$. Figure 1 shows the Ca II H line region for HD 142, together with the quiet Sun and HD 23079. The absence of significant emission confirms that this star is chromospherically inactive.

HD 23079 (HIP 17096, LTT 1739) is an inactive dwarf with a R'_{HK}=−4.96 (Tinney et al. 2002; Henry et al. 1996). Houck & Cowley (1975) classify it as F8/G0V (i.e. intermediate between F8 and G0). Its Hipparcos parallax is 28.9±0.6 mas, giving it M_V=4.42±0.05 and M_{bol}=4.25±0.05 (ESA 1997; Lang 1992). No metallicity information is available for this star, so mass estimation will be less precise. At [Fe/H]=+0.25, 0.0 and −0.25, the models of Fuhrmann et al. (1998, 1997) would indicate M=1.25, 1.10 and 1.0 $M_\odot$ (respectively). For the most likely metallicity range of this F/G-dwarf, its mass lies in the range 1.0-1.25 $M_\odot$, and we therefore adopt M=1.10±0.15 $M_\odot$. Both HD 142 and HD 23079 were seen to be photometrically stable over the life of the Hipparcos mission at a 95% confidence level of <0.018 magnitudes (ESA 1997).

3. RADIAL VELOCITY OBSERVATIONS AND ORBITAL SOLUTIONS

Twenty-seven observations of HD 142 are listed in Table 1. The column labelled "Uncertainty" is the velocity

[1] Based on observations obtained at the Anglo–Australian Telescope, Siding Spring, Australia.

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uncertainty produced by our least-squares fitting. This fit simultaneously determines the Doppler shift and the spectrograph point-spread function (PSF) for each observation made though the iodine cell, given an iodine absorption spectrum and an "iodine free" template spectrum of the object (Butler et al. 1996). The uncertainty is derived from the ensemble of velocities from each of four hundred useful spectral regions (each 2 Å long) in every exposure. This uncertainty includes the effects of photon-counting uncertainties, residual errors in the spectrograph PSF model, and variation in the underlying spectrum between the template and "iodine" epochs. All velocities are measured relative to the zero-point defined by the template observation. Only observations where the uncertainty is less than twice the median uncertainty are listed. These data are shown in Figure 2. The figure shows the best-fit Keplerian model for the data, with the resultant orbital parameters listed in Table 2.

The residuals about the fit are slightly higher than the 3-4 $\mathrm{m\,s^{-1}}$ average level of "jitter" expected in a G1 star with HD 142's level of activity (Saar et al. 1998), but is within the typical range seen in even inactive stars[9].

The thirteen observations of HD 23079 are listed in Table 3, and they are shown in Figure 3 along with a Keplerian fit to the data with the orbital parameters listed in Table 2. The rms scatter about this fit of only 3.08 $\mathrm{m\,s^{-1}}$ demonstrates the extra-ordinary control over long term systematics which the iodine cell technique can deliver for stars with suitable intrinsic velocity stability. It also demonstrates the suitability of the UCLES spectograph at the AAT for radial velocities at the highest precisions – even for a V=7.1 star near our V=7.5 current survey limit.

4. DISCUSSION

The resultant minimum companion mass for HD 142 is $M\sin i = 1.03{\pm}0.19\,M_{JUP}$, with an orbital semi-major axis $a = 1.0{\pm}0.1$ au at an eccentricity of $e = 0.37{\pm}0.1$ – a roughly Jupiter-mass giant planet in an Earth-like, but eccentric, orbit. An interesting feature of HD 142 is that its metallicity is only marginally enriched over solar. This planet, at least, has not formed in a metal-enriched system, as has been suggested for many of the extra-solar planets (e.g. see Gonzalez et al. (2001) and references therein).

The minimum companion mass and orbital parameters derived for HD 23079 ($M\sin i{=}2.5{\pm}1.1\,M_{JUP}$, $a{=}1.5{\pm}0.2$ au, $e{=}0.04{\pm}0.18$) indicate the presence of a planet with significantly larger mass than Jupiter, in a Mars-like orbit with eccentricity consistent with zero. Together with the extra-solar planetary companions to ϵ Ret (Butler et al. 2001), HD 4208 (Vogt et al. 2002), 47 UMa b & c (Fischer et al. 2002), and possibly the companions to HD 114783 and HD 10697 (Vogt et al. 2002, 2000), HD 23079 forms a new class of extra-solar planets, which we name after the prototype object ϵ Ret. The region of the Log(e) versus Log(a_{maj}) diagram these "ϵ Ret-like" planets occupy is highlighted in Fig. 4. It is worth remembering that prior to about 12 months ago the highlighted region of this plot was empty – though many extra-solar planets had been discovered, none shared orbital properties with the planets of our own Solar System. The "ϵ Ret-like" planets, therefore, join with the "51 Peg-like" and eccentric giant planets in filling out the bestiary of extra-solar planets. Prior to their detection, it was unclear whether giant planets in circular, or near-circular, orbits outside 0.1 a.u. would be found *at all* outside the Solar System. Their discovery points the way to the detection of Solar System analogs (in the form of Jupiter-like-planets in Jupiter-like-orbits) once data sequences at better than 2-3 $\mathrm{m\,s^{-1}}$ span the necessary 10-12 year periods.

5. CONCLUSIONS

We present results for the detection and characterisation for two new extra-solar planets with orbital periods of one year or greater around the stars HD 142 and HD 23079. The planet around HD 23079 is particularly interesting – it represents the detection of a new member of the class of "ϵ Ret-like" giant planets in near-circular orbits outside 0.1 a.u.. The continued detection by high precision Doppler searches of these gas giants, in Solar System-like orbits, gives added impetus that the continuation of these searches to the 10-12 year periods where analogs of the gas giants in our own Solar System may become detectable around other stars.

The Anglo-Australian Planet Search team would like to gratefully acknowledge the support of Dr Brian Boyle, Director of the AAO, and the superb technical support which has been received throughout the programme from AAT staff - in particular E.Penny, R.Patterson, D.Stafford, F.Freeman, S.Lee, J.Pogson and G.Schafer. We further acknowledge support by; the partners of the Anglo-Australian Telescope Agreement (CGT,HRAJ,AJP); NASA grant NAG5-8299 & NSF grant AST95-20443 (GWM); NSF grant AST-9988087 (RPB); and Sun Microsystems. NSO/Kitt Peak FTS data used here were produced by NSF/NOAO.

REFERENCES

Alonso, A., Arribas, S. & Martínez-Roger, C. 1995, A&A, 297, 197
Butler, R.P., Marcy, G.W., Williams, E., McCarthy, C. & Dosanjh, P. 1996, PASP, 108, 500
Butler, R.P., Tinney, C.G., Marcy, G.W., Jones, H.R.A., Penny, A.J., Apps, K. 2001, ApJ, 555, 410 (Paper II)
ESA, 1997, The Hipparcos and Tycho Catalogues, ESA SP-1200
Eggen, O.J. 1998, AJ, 115, 2397
Favata, F., Micela, G. & Sciortino, S. 1997, A&A, 323, 809
Fischer, D. A., Marcy, G. W., Butler, R. P., Vogt, S. S., Frink, S., & Apps, K. 2001, ApJ, 551, 1107
Fischer D., Marcy G., Butler P., Laughlin G. & Vogt S., 2002, ApJ, in press.
Fuhrmann, K., Pfeiffer, M.J. & Bernkopf, J. 1997 A&A, 326, 1081
Fuhrmann, K., Pfeiffer, M.J. & Bernkopf, J. 1998 A&A, 336, 942
Gonzalez G., Laws C., Tyagi S., Reddy B. E., 2001, AJ, 121, 432
Henry, T.J., Soderblom, D.R., Donahue, R.A. & Baliunas, S.L. 1996, AJ, 111, 439.
Houck, N. and Cowley, A.P. 1975, Michigan Catalogue of Two Dimensional Spectral Types for the HD stars, Volume 1, Michigan Spectral Survey: Ann Arbor

[9] "Jitter" here is used to refer to the scatter in the observed velocity about a mean value in systems observed over the long-term to have no Keplerian Doppler shifts, or about a fitted Keplerian in systems known to have a planetary mass companion. It is thought to be due to the combined effects of surface inhomogeneties, stellar activity and stellar rotation.

Houck, N. 1978, Michigan Catalogue of two dimentional spectral types for the HD stars, Volume 2, Michigan Spectral Survey: Ann Arbor

Kurucz, R.L., Furenlid, I. Brault, J. & Testerman, L. 1984, Solar Flux Atlas from 296 to 1300 nm, National Solar Observatory Atlas No. 1

Lang, K.R. 1992, Astrophysical Data: Planets and Stars, Springer-Verlag: New York

Saar, S.H., Butler, R.P. & Marcy, G.W. 1998, ApJ, 403, L153

Tinney, C.G., Butler, R.P., Marcy, G.W., Jones, H.R.A., Penny, A.J. Vogt, S.S., Apps, K. & Henry, G.W. 2001, ApJ, 551, 507 (Paper I)

Tinney, C.G., McCarthy, C., Jones, H.R.A., Butler, R.P., Carter, B.D., Marcy, G.W., & Penny, A.J. 2002, MNRAS, (submitted)

Vogt, S.S., Marcy, G.W., Butler, R.P. & Apps, K. 2000, ApJ, 536, 902

Vogt, S.S., Butler, R.P., Marcy, G.M., Fischer, D.A., Pourbaix, D. Apps, K., Laughlin, G. 2002, ApJ, submitted `http://xxx.lanl.gov/abs/astro-ph/0110378`.

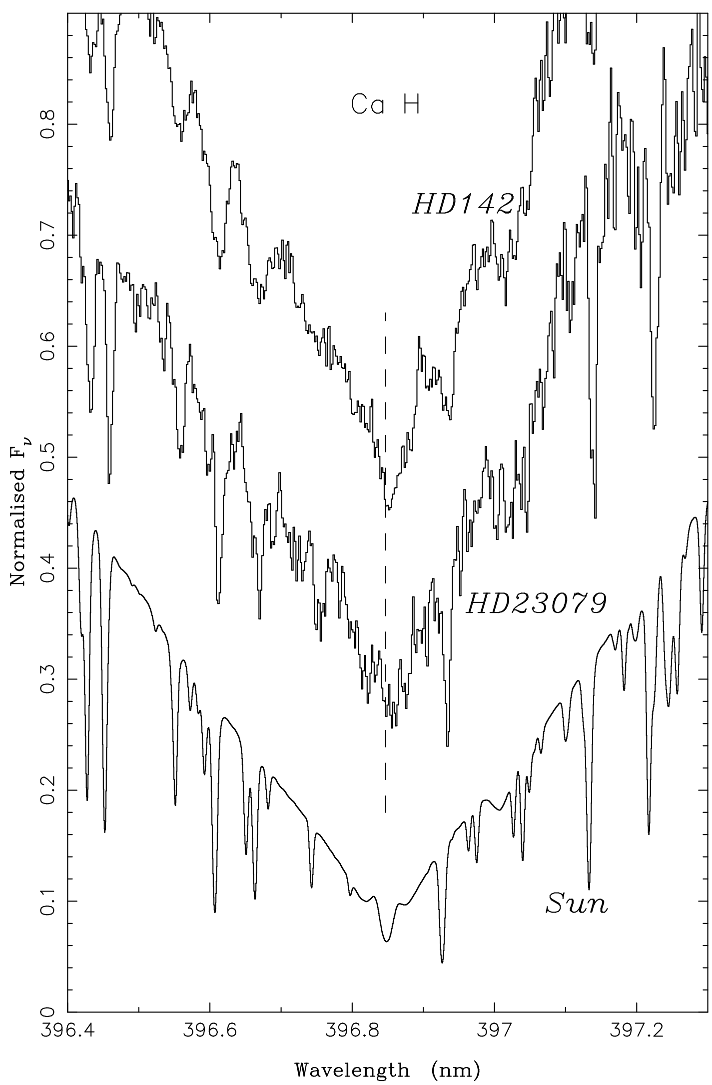

Fig. 1.— Comparison of the Ca II H line core in the Sun (lower line), HD 23079 (middle line) and HD 142 (upper line). Solar spectrum is from Kurucz et al. (1984) and other spectra are from Tinney et al. (2002).

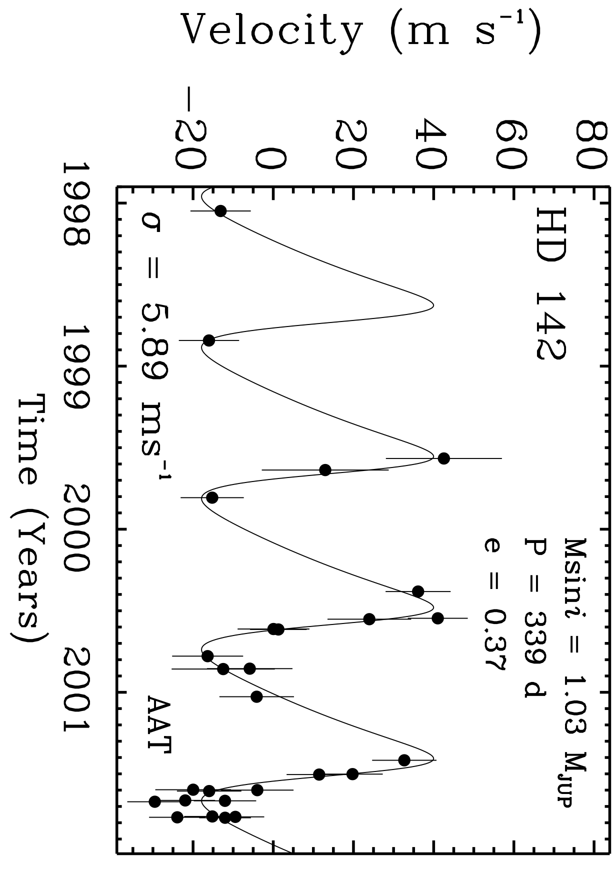

FIG. 2.— AAT Doppler velocities for HD 142 from 1998 January to 2001 October. The solid line is a best fit Keplerian with the parameters shown in Table 2.The rms of the velocities about the fit is 5.89 m s^{-1}. Assuming 1.15 M$_{\odot}$ for the primary, the minimum (M sin i) mass of the companion is 1.03±0.19 M$_{\rm JUP}$, and the semimajor axis is 1.0±0.1 au.

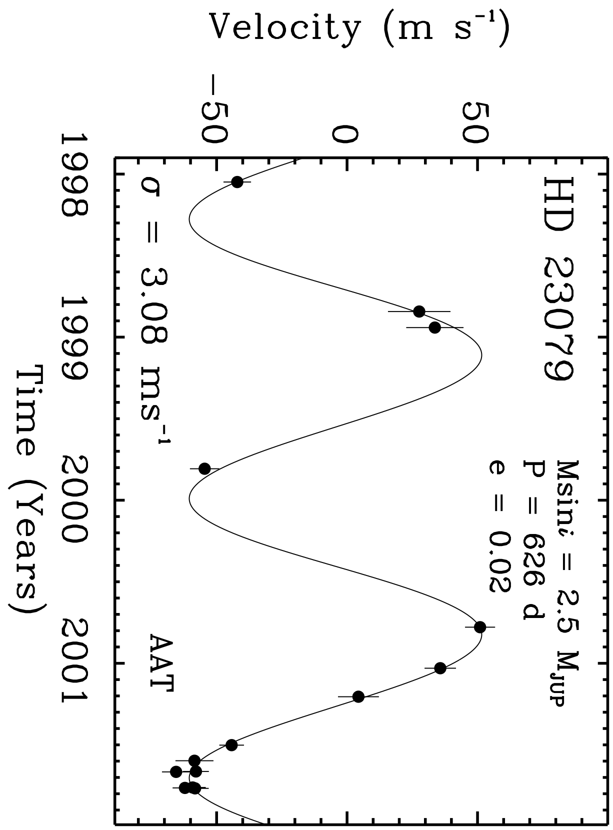

FIG. 3.— AAT Doppler velocities for HD 23079 from 1998 January to 2001 October. The solid line is a best fit Keplerian with the parameters shown in Table 2. The rms of the velocities about the fit is $3.08\,\mathrm{m\,s^{-1}}$. Assuming a $1.1\,\mathrm{M_{\odot}}$ for the primary, the minimum ($\mathrm{M}\sin i$) mass of the companion is $2.5{\pm}0.3\,\mathrm{M_{JUP}}$, and the semimajor axis is $1.5{\pm}0.2$ au.

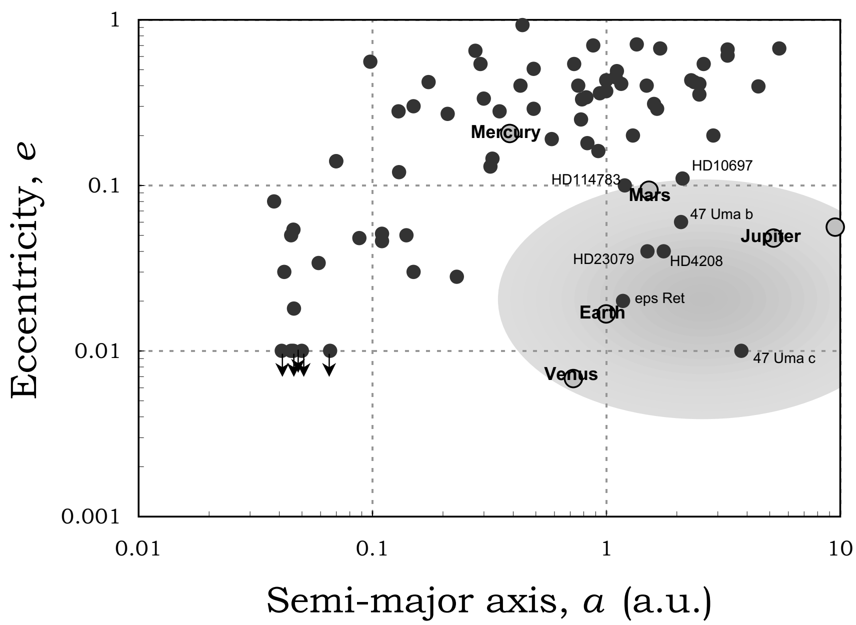

FIG. 4.— Log(e) versus Log(a) for extra-solar planets reported as of 2001 September, plus the new planets reported in this paper and by (Vogt et al. 2002) *(solid circles)*, together with the inner planets of the Solar System *(shaded circles)*. Planets with measured eccentricities $e < 0.01$ are shown as upper limits at $e = 0.01$. The region of the Log(e)-Log(a) occupied by the planets of the Solar System, and its similarity to those of the "ϵ Ret-like" planets is highlighted.

Table 1
Velocities for HD 142

JD[a] (-2450000)	RV[a] ($m\,s^{-1}$)	Uncertainty ($m\,s^{-1}$)
830.9587	-13.1	7.5
1121.0194	-16.0	7.5
1385.3105	42.6	14.5
1411.2025	13.0	15.8
1473.0850	-15.2	7.9
1683.3314	36.1	8.1
1743.2765	41.0	7.5
1745.2642	24.0	10.4
1767.2699	0.1	9.0
1768.2542	1.3	7.1
1828.0607	-16.4	8.9
1856.0643	-5.9	10.7
1856.9250	-12.5	12.9
1918.9407	-4.1	9.3
2061.2963	32.7	8.0
2092.2683	19.8	7.5
2093.2876	11.4	8.1
2127.2230	-20.0	9.4
2128.1545	-4.0	9.0
2130.2433	-16.0	8.0
2151.2113	-21.9	7.4
2152.0786	-12.0	7.8
2154.1541	-29.5	6.9
2187.1000	-15.2	7.0
2188.0360	-9.4	7.2
2189.0199	-23.9	7.0
2190.0032	-12.0	6.4

[a]Radial Velocities (RV) are barycentric, but have an arbitrary zero-point determined by the radial velocity of the template, as described in Section 3

Table 2
Orbital Parameters

Parameter	HD 142	HD 23079
Orbital period P (d)	339±6	626±24
Velocity amp. K ($\mathrm{m\,s^{-1}}$)	29.6±5	56±5
Eccentricity e	0.37±0.1	0.02±0.12
ω (°)	71±36	262±50
$a_1 \sin i$ (km)	$(0.1280\pm0.0066)\times10^6$	$(0.482\pm0.019)\times10^6$
Periastron Time (JD-2450000)	1752±22	1680±90
$\mathrm{M} \sin i$ ($\mathrm{M_{JUP}}$)	1.03±0.19	2.5±0.3
a (AU)	1.0±0.1	1.5±0.2
RMS about fit ($\mathrm{m\,s^{-1}}$)	5.89	3.08

Table 3
Velocities for HD 23079

JD[a] (-2450000)	RV[a] ($\mathrm{m\,s^{-1}}$)	Uncertainty ($\mathrm{m\,s^{-1}}$)
831.0689	-42.1	5.3
1121.1268	27.7	12.0
1157.0594	33.6	11.0
1473.2492	-54.6	5.6
1828.1399	51.0	5.8
1920.0142	35.7	6.0
1983.8858	4.4	7.8
2092.3211	-44.2	4.7
2127.2797	-58.5	7.3
2151.2764	-57.9	5.0
2152.2093	-65.5	5.4
2187.1679	-59.2	5.0
2188.1270	-62.1	4.7
2189.1418	-58.3	5.2

[a]As for Table 1